

NHDOT SPR2 PROGRAM

RESEARCH PROGRESS REPORT

Project # 269620		Report Period: Year: 2019 <input checked="" type="checkbox"/> Q1 (Jan-Mar) <input type="checkbox"/> Q2 (Apr-Jun) <input type="checkbox"/> Q3 (Jul-Sep) <input type="checkbox"/> Q4 (Oct-Dec)	
Project Title: Incorporating Impact of Aging on Cracking Performance of Mixtures during Design			
Project Investigator: Jo E. Sias (Co-PI: Eshan Dave) Phone: 603-862-3277 E-mail: jo.sias@unh.edu			
Research Start Date: December 1, 2016	Research End Date: June 30, 2019	Project schedule status: <input checked="" type="checkbox"/> On revised schedule <input type="checkbox"/> Ahead of schedule <input type="checkbox"/> Behind schedule	

Progress this Quarter (include meetings, installations, equipment purchases, significant progress, etc.):

The work conducted this quarter has focused on the testing and analysis of field cores from the Westmoreland project and the binder samples extracted and recovered from five mixtures (5834LM, 6428SV, 6428SM, 7034LV and 762SM). The detailed result and discussion are shown in Appendix.

Table 1 below shows the status summary for the project mixture testing. The complex modulus, disc-shaped compact tension (DCT) and semicircular bending (SCB) fracture testing are completed for all the mixtures. The S-VECD fatigue testing for all but the 5834LM mixture have been completed at the different aging levels.

Table 1- Status Summary for Project Mixtures

Mixture ID	Binder PG Grade	NMAS (mm)	%TRB	Status						
				Received	Aging	Testing/Analysis				
						STA	95°C@5d	85°C compacted	95°C@12d	135°C@24hr.
5828LL (WM-S-1)	PG 58-28	12.5	1.5							
5828LM (WM-S-2)	PG 58-28	12.5	1.0							
5234LM (WM-S-3)	PG 52-34	12.5	1.0							
5234LL (WM-S-4)	PG 52-34	12.5	1.5							
5828SM (S-1)	PG 58-28	9.5	1.0					NA		
6428SM (T4)	PG 64-28	9.5	1.0					NA		
7628SM (SHS-1)	PG 76-28	9.5	1.0					NA		
7034LV (SHM-1)	PG 70-34	12.5	0					NA		
6428SV (SV-1)	PG 64-28	9.5	0					NA		
5834LM (T3)	PG 58-34	12.5	1.0					NA		
6428LM (T5)	PG 64-28	12.5	1.0					NA		

Completed ■ In Progress ■ Not Started ■

Table 2 below shows the testing that is being conducted on the extracted and recovered binders. The bending beam rheometer (BBR) and extended bending beam rheometer (EBBR) tests were done by NHDOT and the dynamic shear rheometer (DSR) testing by UNH. The 4mm DSR testing on the binder samples extracted and recovered from the project mixtures have been completed. The field cores from these Westmoreland mixtures has been sent to NHDOT for extraction

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and recovery. Tables 3 and 4 show the status of the extracted and recovered binder testing. Also, seven binder samples from the 2017 paving projects were received by UNH, and the 4mm DSR testing has been completed for these binder samples and compared with the NHDOT BBR results (the results were presented in the previous quarterly report Q2). Table 5 shows the summary status for the binders sampled during production.

Table 2- Summary Table for Binder Tests

Tests	Virgin Binder (Sampled during production)	STOA	LTOAs	Field Cores
25mm DSR				
8mm DSR				
4mm DSR				
BBR				
EBBR				

Included ■ Not Included in Study ■

Table 3- Status Summary for Extracted and Recovered Binders from Lab Aged Mixtures

Binder Type	Mixture ID	NMAS (mm)	%TRB	Status					
				Sent to NHDOT for Extraction /Recovery	Extracted Binder received by UNH	Testing/Analysis			
						STOA	95°C@5d	95°C@12d	135°C@ 24hr.
PG 58-28	5828LL	12.5	1.5				NA		
PG 58-28	5828LM	12.5	1.0				NA		
PG 52-34	5234LM	12.5	1.0						
PG 52-34	5234LL	12.5	1.5						
PG 58-28	5828SM	9.5	1.0	NA	NA	NA	NA	NA	NA
PG 64-28	6428SM	9.5	1.0						NA
PG 76-28	7628SM	9.5	1.0						NA
PG 70-34	7034LV	12.5	0						NA
PG 64-28	6428SV	9.5	0						NA
PG 58-34	5834LM	12.5	1.0						NA
PG 64-28	6428LM	12.5	1.0	NA	NA	NA	NA	NA	NA

Completed ■ In Progress ■ Not Started ■

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Table 4- Status Summary for Extracted and Recovered Binders from Field Cores

Binder Type	Mixture ID	NMAS (mm)	%TRB	Status		
				Sent to NHDOT for Extraction /Recovery	Extracted Binder received by UNH	Testing/Analysis
PG 58-28	5828LL	12.5	1.5			
PG 58-28	5828LM	12.5	1			
PG 52-34	5234LM	12.5	1			
PG 52-34	5234LL	12.5	1.5			

Tested by UNH ■ In Progress ■ Not Started ■

Table 5- Summary Table for Production Virgin Binder Samples

Binder Type	Mixture ID	NMAS (mm)	%TRB	Sampled Binder Received by UNH	Status			
					Testing/Analysis			
					Original	RTFO	PAV	
							BBR/8mm DSR	4mm DSR
PG 58-28	5828LL	12.5	1.5	NA				NA
PG 58-28	5828LM	12.5	1.0	NA				NA
PG 52-34	5234LM	12.5	1.0	NA				NA
PG 52-34	5234LL	12.5	1.5	NA				NA
PG 58-28	5828SM	9.5	1.0					
PG 64-28	6428SM	9.5	1.0					
PG 76-28	7628SM	9.5	1.0					
PG 70-34	7034LV	12.5	0					
PG 64-28	6428SV	9.5	0					
PG 58-34	5834LM	12.5	1.0					
PG 64-28	6428LM	12.5	1.0					

Tested by NHDOT ■ Tested by UNH ■ In Progress ■ Not Started ■

The complex modulus, S-VECD fatigue, and SCB testing were conducted on the field cores from the Westmoreland field sections. Table 6 below shows the testing status on these field cores. The detailed results (SCB) are presented in the Appendix in this report.

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Table 6- Summary Table for Field Cores

Mixture ID	Binder Type	NMAS (mm)	%TRB	Status		
				Testing/Analysis		
				Complex Modulus	S-VECD Fatigue	SCB
WM-S-1	PG 58-28	12.5	1.5			
WM-S-2	PG 58-28	12.5	1.0			
WM-S-3	PG 52-34	12.5	1.0			
WM-S-4	PG 52-34	12.5	1.5			

Completed ■ In Progress ■ Not Started ■

Items needed from NHDOT (i.e., Concurrence, Sub-contract, Assignments, Samples, Testing, etc...):

Extracted and recovered binders from the field cores indicated in Table 4.

Anticipated research next 3 months:

In the coming quarter, the research group plans to finish all the remaining laboratory testing of the mixtures and binders, develop the screening tool and guidelines for material selection and mix design, and write the final report.

Circumstances affecting project: Describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope, and budget, along with recommended solutions to those problems.

The characterization of extracted and recovered binders is behind schedule due to time needed by NHDOT to work through with the extraction and recovery of these materials. As a result of this delay the project has been extended until June 30, 2019.

Tasks (from Work Plan)	Planned % Complete	Actual % Complete
Literature Review and Testing Plan	100	100
Laboratory Aging of Mixtures	100	100
Mixture Material Characterization Testing and Analysis	100	99
Characterization of Extracted and Recovered Binders and Analysis	100	85
Development of Screening Tool and Guidelines	100	50
Reporting	0	0

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Appendix:

Results and Discussion

SCB on Field Cores

Figure 1 below shows the flexibility index (FI) measured from the SCB test for the four Westmoreland mixtures, as well as the corresponding field cores (four years in service). The mixture with the same binder grade shows the lower FI value with increase of RAP content for both lab aged mixtures and filed cores. The FI value for the field cores is generally higher than the lab aged mixtures. One possible explanation is that the relatively higher air void of the SCB samples from the field cores (average 7.5-10.5% in table 7) compared to the lab aged mixtures (approximately 6%), as well as the aging gradient in the field cores (pavement) may lead to the difference of FI value. UNH research team will further evaluate and compare the lab aging methods with field aging duration by conducting the DSR test on the binder samples extracted and recovered from various layers within these field cores.

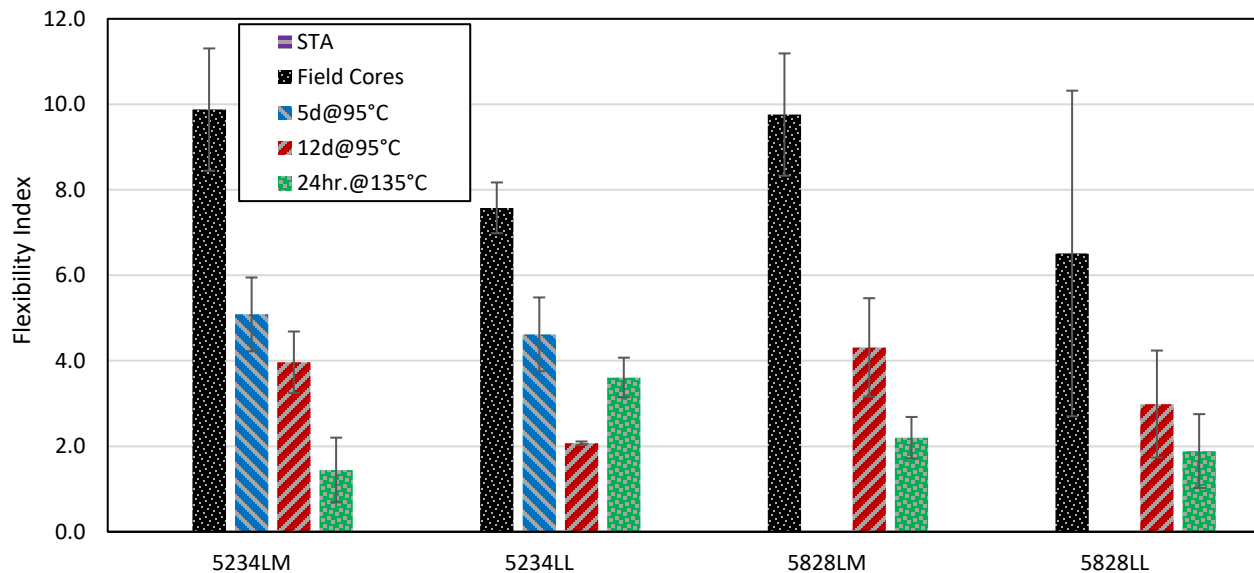


FIGURE 1 Comparison of FI Values for Four Westmoreland Mixtures with Field Cores

Table 7- Summary Table of Air Void for SCB samples from Field Cores

MIX ID	5234LM	5234LL	5828LM	5828LL
Replicate 1	7.23%	9.03%	12.00%	8.06%
Replicate 2	7.47%	9.31%	12.12%	8.24%
Replicate 3	12.12%	11.38%	3.89%	7.39%
Replicate 4	14.18%	11.40%	2.82%	7.49%
Average	10.25%	10.28%	7.71%	7.79%

Binder Testing Results

The results of 4mm DSR testing (following the MTE method) conducted for the binder samples extracted and recovered from the five mixtures are presented and discussed in this section.

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$|G^*|$ and Phase Angle

Complex shear modulus and phase angle mastercurves constructed from the 4mm DSR testing are presented as the average of three replicates for the binder samples extracted from the five mixtures in Figures 2 and 3. Generally, complex modulus increases as the aging level increases, while phase angle decreases as materials age. Both the complex modulus and phase angle for the different aging levels collapse together at high frequencies (higher than 10^6 Hz). As materials age, complex modulus curve becomes flat, while the peak value of the phase angle curve moves down and left (lower frequencies). The 7034LV has a steeper complex modulus curve than the other four types of binder at each aging condition. The trend from binder test results is similar to those observed from the mixture complex modulus (E^*) testing.

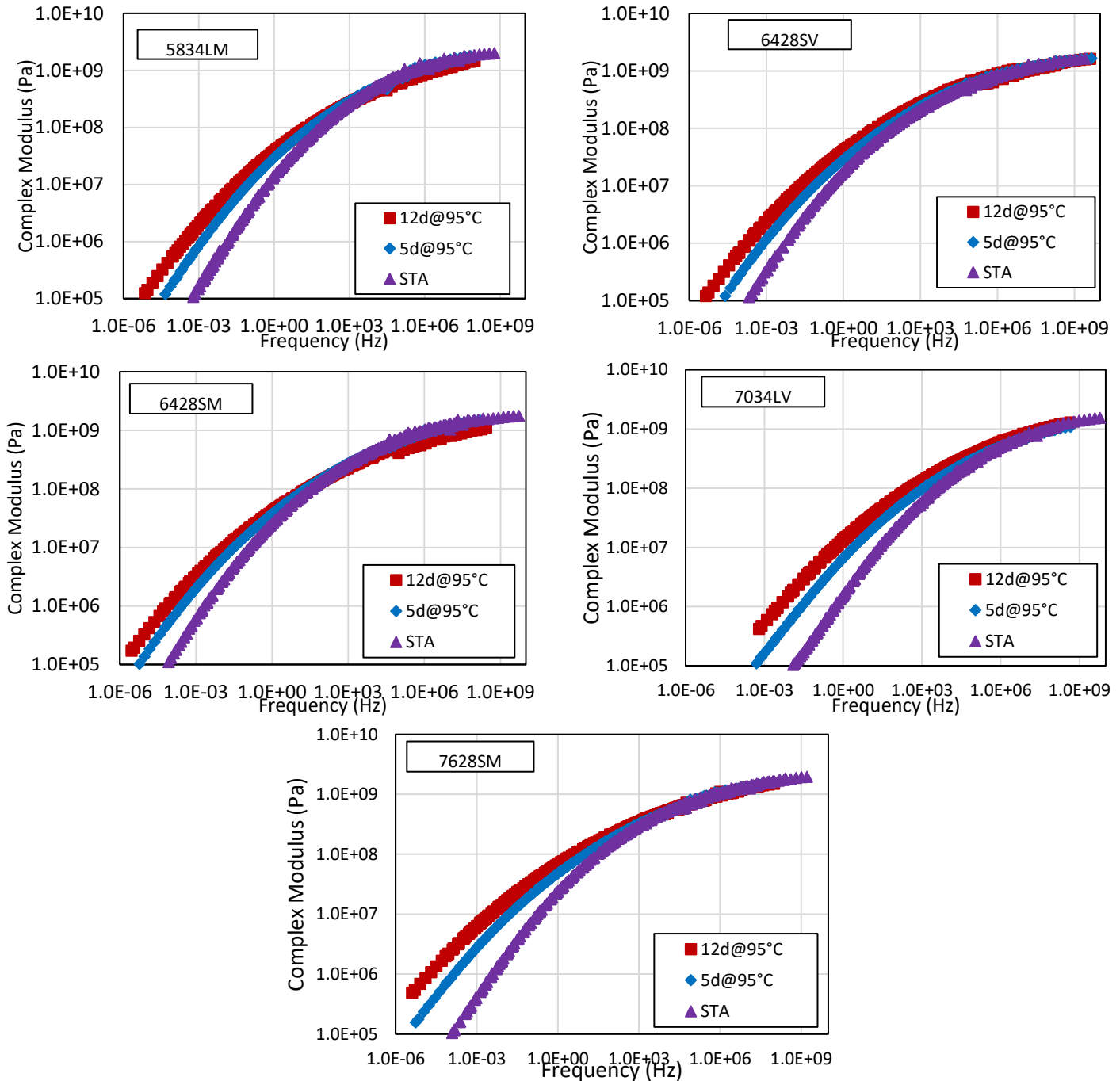


FIGURE 2 Complex Shear Modulus Master Curves for Extracted and Recovered Binder Samples

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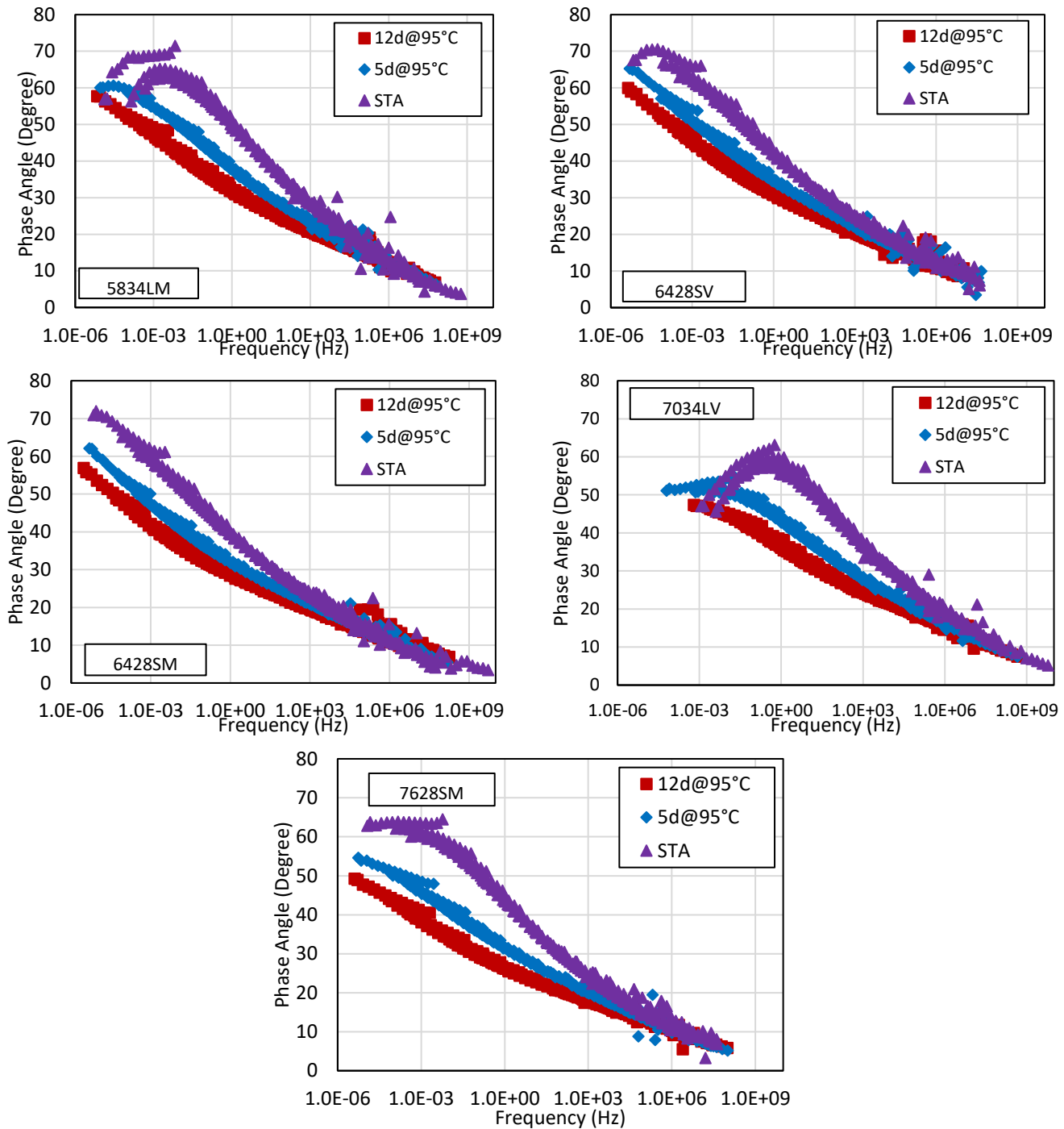


FIGURE 3 Phase Angle Master Curves for Extracted and Recovered Binder Samples

PGLT (Performance Grade Low Temperature)

Figure 4 shows the average PGLT and the change of the PGLT (LTOAs minus STA) from 3 replicates determined from the 4mm DSR tests. Error bars show one standard deviation. Generally, PGLT and the change in PGLT from STA increase as aging level increases. There is a statistically significant difference in PGLT between the STA and all other three long-term aging conditions. The PGLT for 5834LM and 7034LV after each aging condition is typically lower than other materials, while 7628SM shows a higher PGLT value with aging. Comparing the change of PGLT for these binder samples, 7628SM clearly shows a larger change than other binders with aging, showing higher aging susceptibility which is consistent with the mixture test results.

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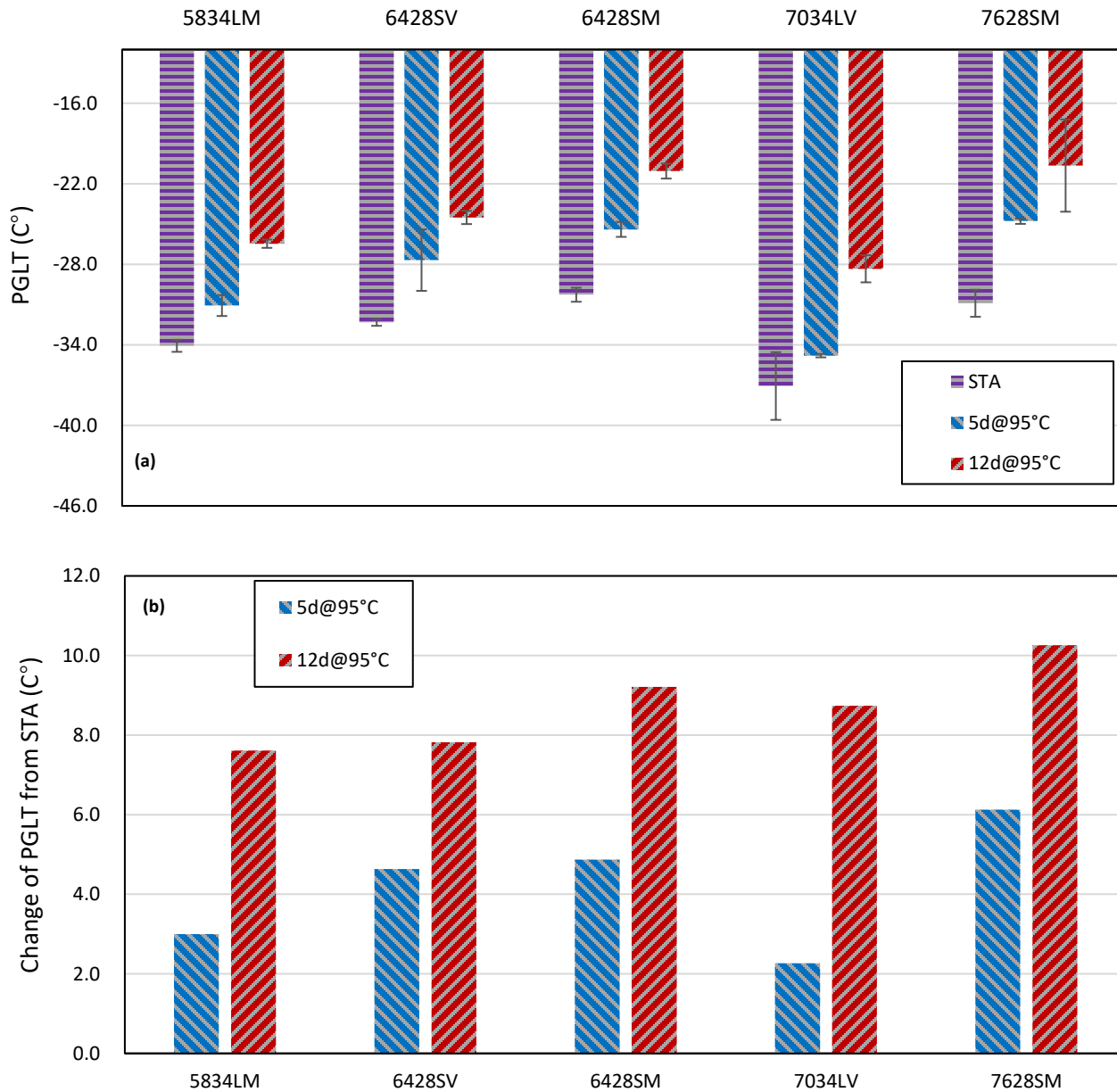


FIGURE 4 a) PGLT and b) Change of PGLT for Different Binder Samples from 4mm DSR Tests

R-value

R-value is the difference between the logarithmic glassy modulus and the logarithmic equilibrium modulus of the binder, simplified as $\text{Log } |G^*| @ \text{glassy asymptote} - \text{Log } |G^*| @ \text{the crossover frequency}$. Figure 5 shows the average R-value and the change of the R-value (LTOAs minus STA). Error bars show one standard deviation. As binder stiffness increases due to aging and oxidation, the R-value increases, resulting in higher cracking susceptibility. Generally, R-value and the change of the R-value from STA increase as aging level increases. There is a statistically significant difference in R-value between the STA and all other three long-term aging conditions. Similar to the PGLT results, 5834LM generally shows lower R value after each aging condition compared with other materials, 7628SM shows greater changes in R-value than others.

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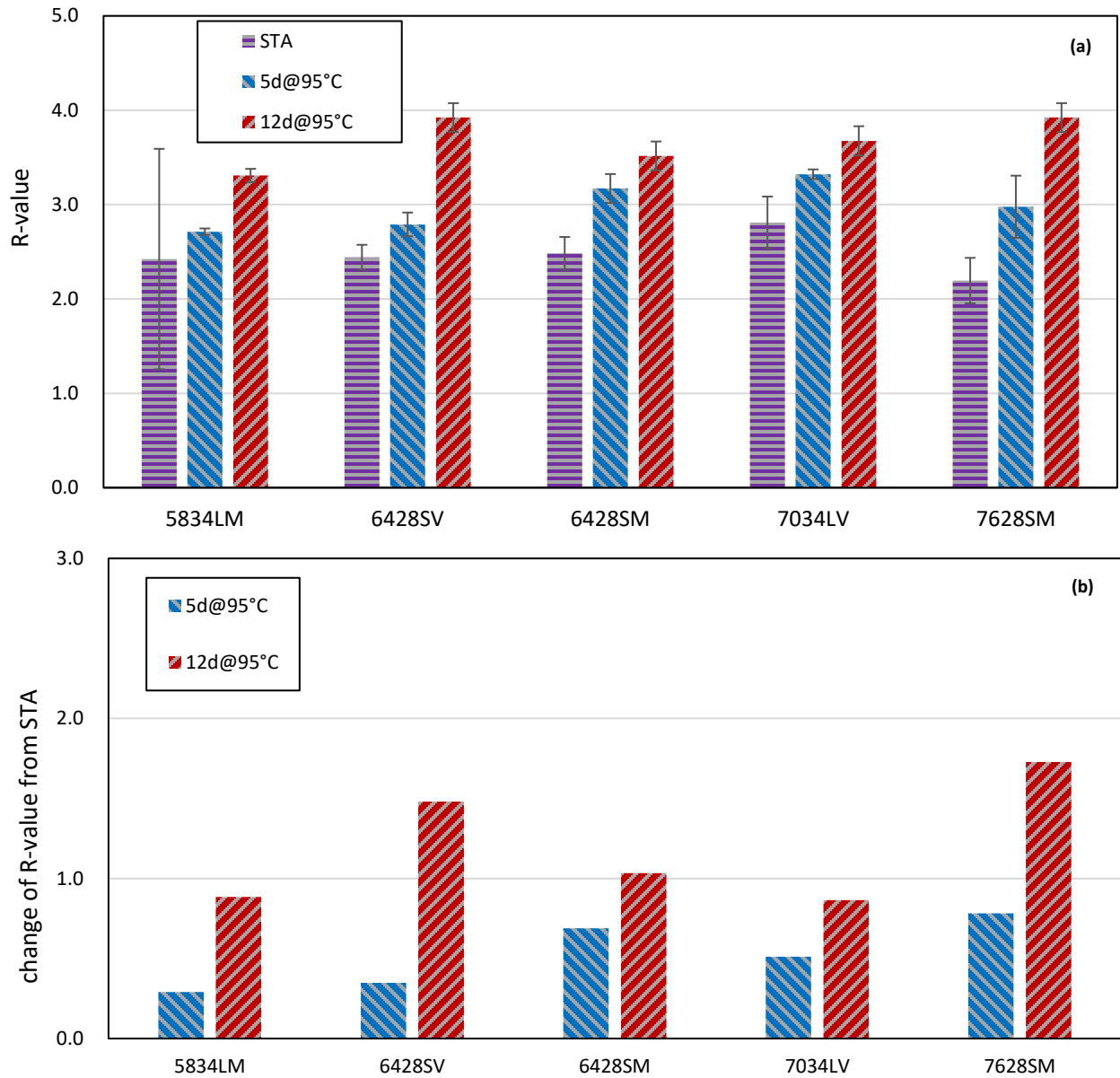


FIGURE 5 a) R-value and b) Change of R-value for Different Binder Samples from 4mm DSR Tests

Different in Critical Cracking Temperatures for Creep Stiffness and Relaxation Parameters (ΔT_c)

ΔT_c is defined as the difference between the temperature at which the creep stiffness, $S(t)$, and m-value criteria from the BBR testing are met. When the ΔT_c value is higher than 0, the binder grade is controlled by the stiffness (S-controlled), but when the ΔT_c value is lower than 0, the binder becomes m-controlled. S-controlled binders have “extra” relaxation capability and are therefore typically less prone to cracking. Asphalt Institute suggests using $\Delta T_c = -2.5^\circ\text{C}$ as a crack warning limit and $\Delta T_c = -5.0^\circ\text{C}$ as the cracking limit, represented by the two red lines in Figure 6.

Figure 6 also shows the average ΔT_c and the change in the ΔT_c (absolute value of LTOAs minus STA). Error bars show one standard deviation. ΔT_c generally decreases as aging level increases, while the change of the ΔT_c increases with increase of aging. There is a statistically significant difference in ΔT_c between the STA and all other three long-term aging conditions. The ΔT_c value for 5834LM and 7034LV after each aging condition is typically higher than other materials. The ΔT_c value for these two binders with different aging levels is also within the cracking limit, while 6428SV, 6428SM and 7628SM exceed

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the cracking limit value after 12 days aging condition. The 7628SM binder shows the good cracking performance with positive ΔT_c value after STA, however, after 5 days and 12 days aging conditioning, it shows the lowest (negative) ΔT_c value. Also, from figure 6b, 7628SM shows a greater change in ΔT_c value compared with other materials, indicating higher aging susceptibility.

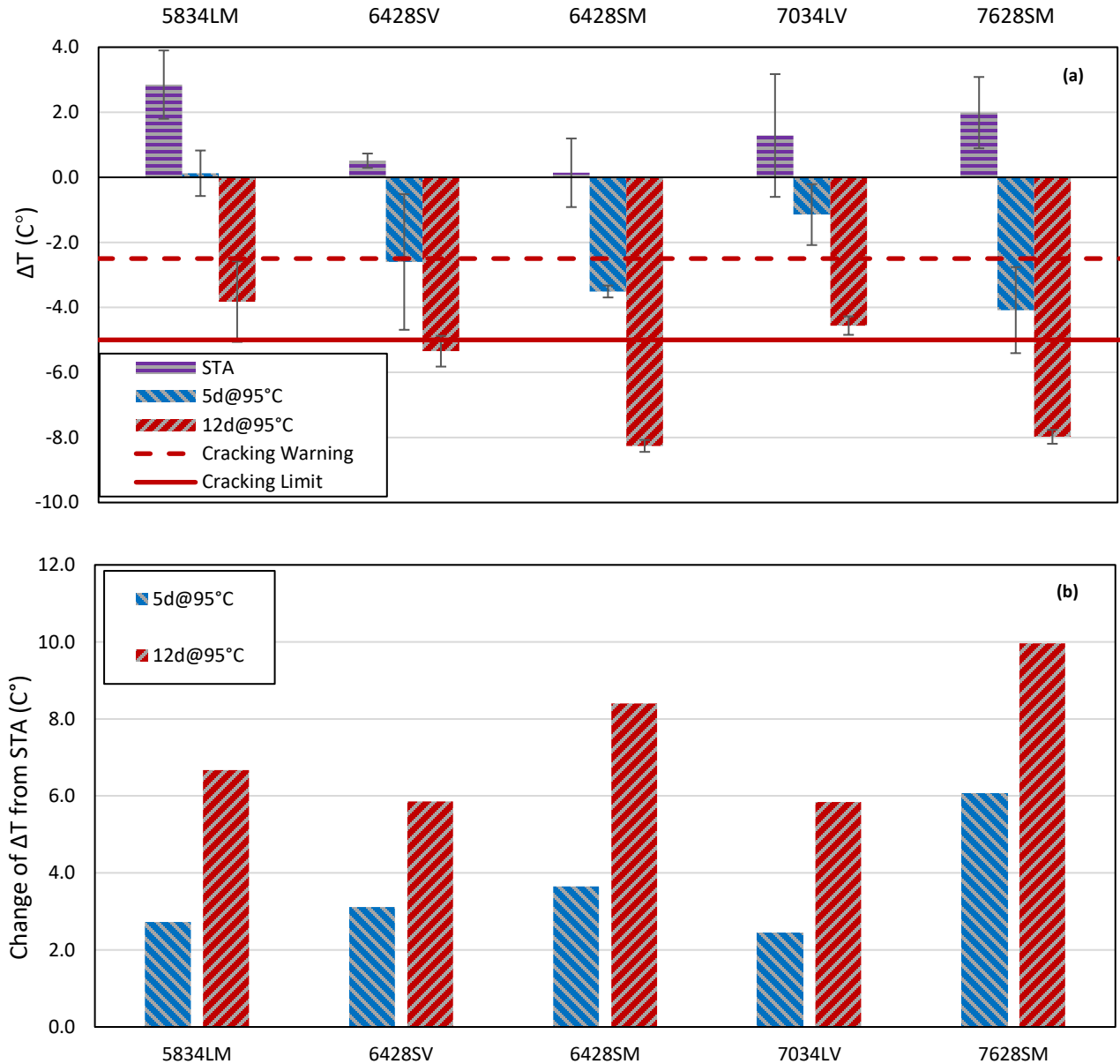


FIGURE 6 a) ΔT_c and b) Change of ΔT_c for Different Binder Samples from 4mm DSR Tests

Glover-Rowe (G-R) Parameter and Black Space

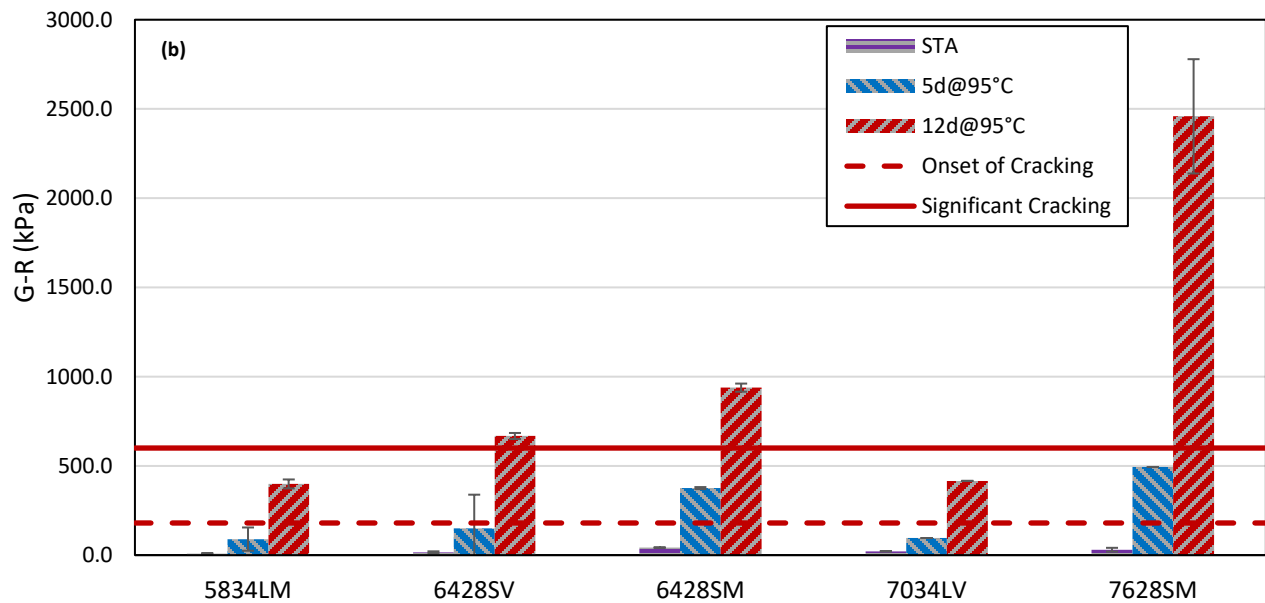
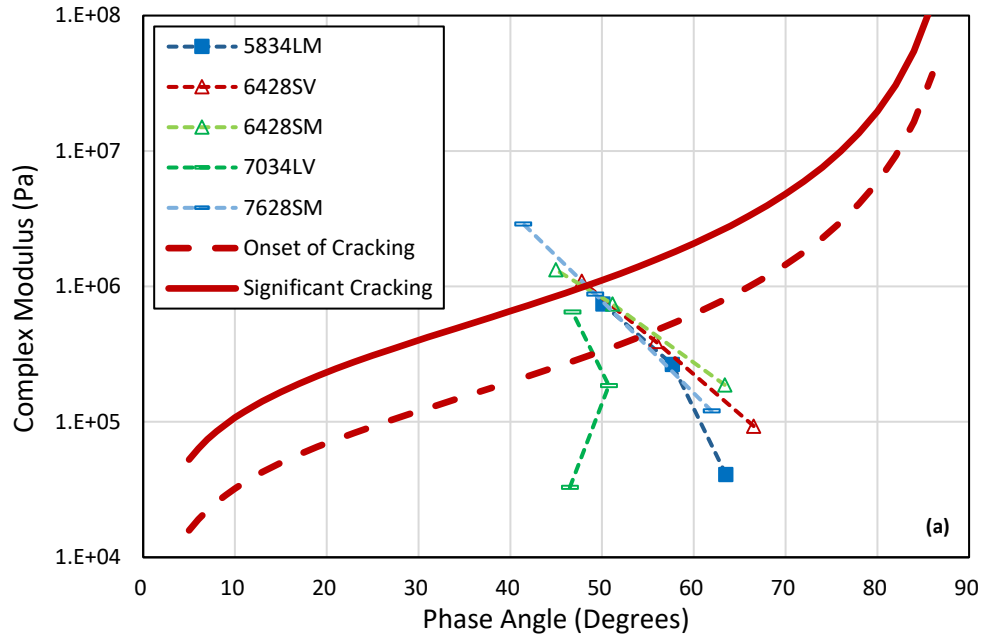
Rowe et al. developed a Glover-Rowe parameter ($\frac{G^*(\cos\delta)^2}{\sin\delta}$, calculated at 15°C, 0.005rad/sec) to evaluate the cracking susceptibility of asphalt binders. A lower G-R parameter indicates better capability to resist durability cracking. A limiting value of 180kPa is proposed for the onset of cracking, a second value of 600kPa is suggested for the development of the significant cracking (block cracking), as the two red lines shown in Figure 7.

Figure 7 shows the average G-R parameter in Black space (a) and on a bar graph (b), as well as the change of the G-R

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parameter (c) (LTOAs minus STA). Error bars show one standard deviation. Generally, G-R parameter and the change of the G-R parameter from STA increase as aging level increases. There is a statistically significant difference in G-R parameter between the STA and all other three long-term aging conditions. Very similar to the ΔT_c result, The G-R parameter for 5834LM and 7034LV after each aging condition is typically lower than other materials, and the values for these two binders with different aging levels are within the significant cracking limit, while 6428SV, 6428SM and 7628SM exceed this cracking limit value after 12 days aging condition. The 7628SM binder shows good cracking performance with very small value of G-R parameter after STA, however, after 5 days and 12 days aging conditioning, it shows higher values compared with other materials. Also, from figure 7c, 7628SM shows a greater change in G-R parameter compared with others, indicating higher aging susceptibility.



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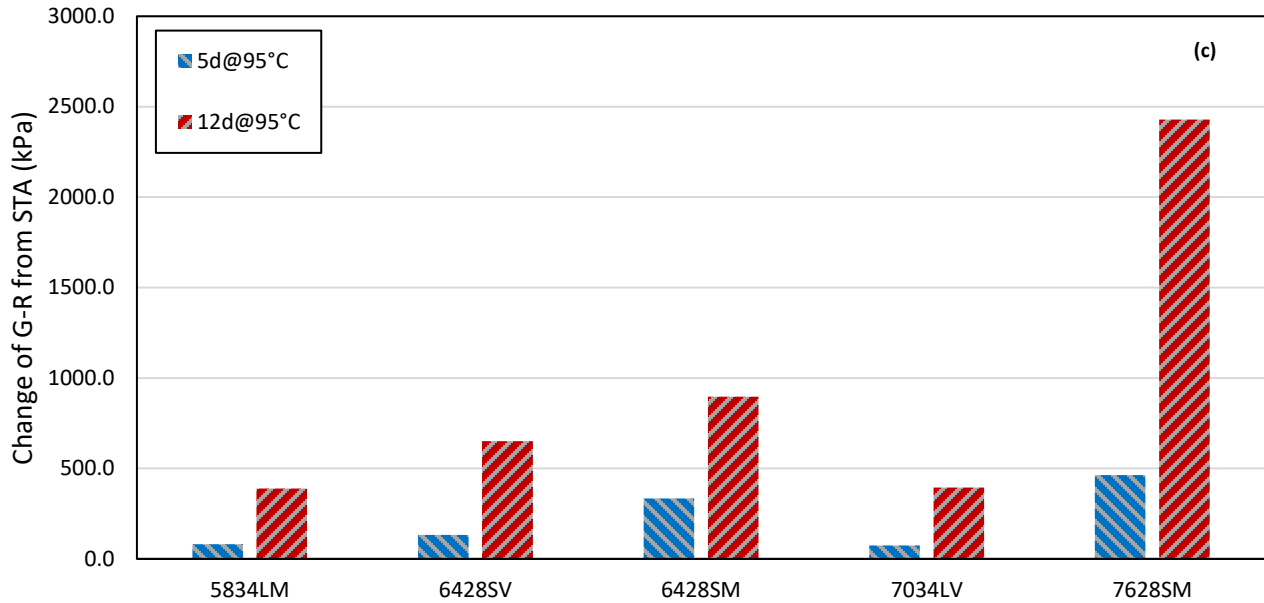


FIGURE 7 a) Black space; b) G-R Parameter; and c) Change of G-R Parameter for Different Binder Samples from 4mm DSR Tests

Combination of ΔT_c and G-R Parameter

As discussed above, ΔT_c and G-R parameter evaluate the ability of binder to resist the thermal cracking and durability (block) cracking, respectively. So, it is important and worthwhile to combine these two parameters together to evaluate the cracking performance of the asphalt binders. Figure 8 below provides a way to combine these two criteria and evaluate the thermal and durability cracking susceptibility of the binders after different aging conditions together. The two red dashed lines represent the cracking warning values for ΔT_c (-2.5°C) and G-R parameter (180kPa) respectively, while the solid red lines represent the cracking limit values for ΔT_c (-5.0°C) and G-R parameter (600kPa). The area surrounded by the two dashed lines at the bottom right of the plot, labelled as the safe zone, means that the binders have adequate capability under intermediate and cold temperature to resist cracking, so that generally, no cracking problems should be expected when the ΔT_c and G-R parameter of the binders fall into this area. However, if the points fall into the failure zone surrounded by the two solid lines at the top left of the plot, it indicates that the binders will have a high susceptibility to both thermal and durability (block) cracking since both ΔT_c and G-R parameter values of the binder samples exceed the cracking limit values.

The STA condition binders generally fall into the safe (cracking free) zone, which means that typically no cracking problems are expected. For 5834LM and 7034LV, after 5 days aging, the points are located in the safe zone, even after 12 days aging condition, the ΔT_c value and G-R parameter are still within the cracking limits. However, 6428SV, 6428SM and 7628SM after 12 days aging condition, fall into the failure zone, which means that there may be significant cracking problems based on the ΔT_c and G-R criteria.

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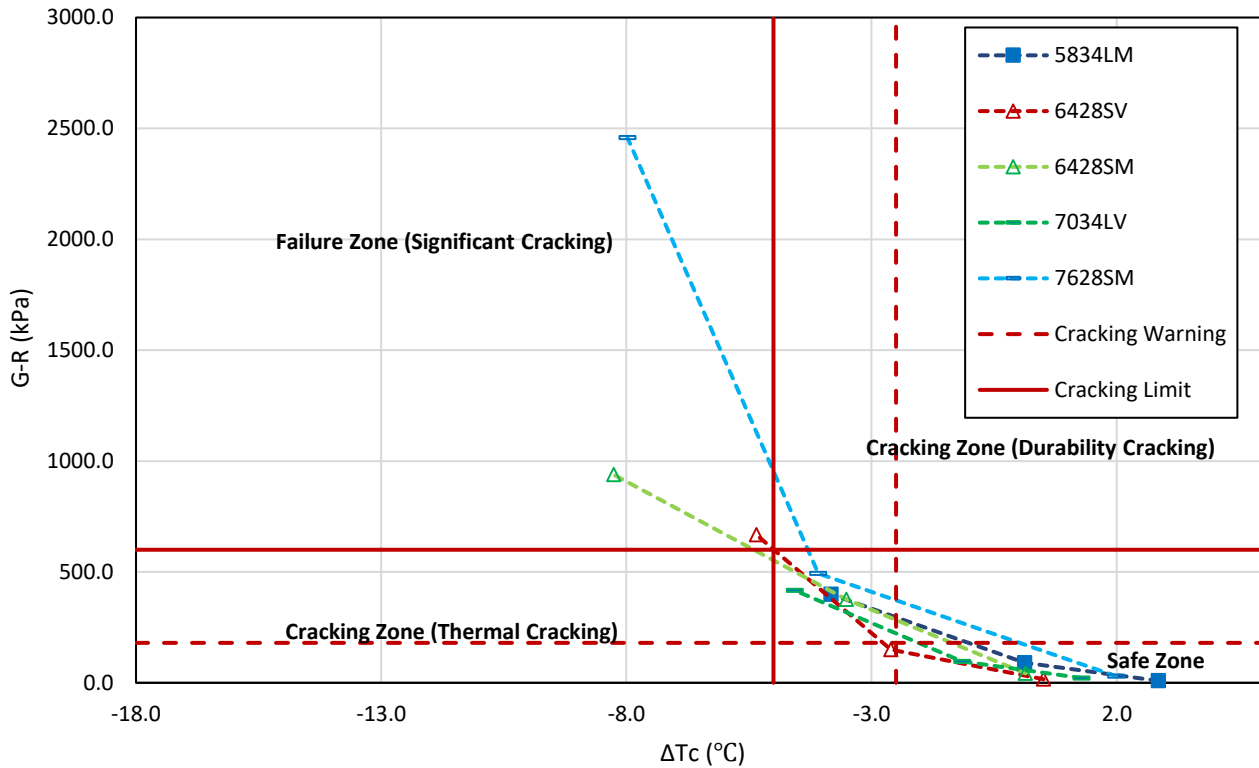


FIGURE 8 Combination of ΔT_c and G-R Criteria

Transition Temperatures (T_g , T_t and T_{IR})

Binder rheological behavior is divided into three regions: Near glassy region, terminal region, and an intermediate “transition” region in between them, as indicated in figure 9. At a reference frequency (generally 10 rad/s or 1.59 Hz for binder), the glass transition temperature (T_g) is a fundamental property of amorphous and semi-crystalline materials, including asphalt binders, which is the temperature between the near glassy region and the intermediate region. Below the glass transition temperature, there is insufficient thermal energy in the material to allow for large-amplitude molecular motion, while crossover (also called visco-elastic transition) temperature (T_t , when $G' = G''$) is the temperature between the intermediate and the terminal regions (Ferry, 1980; Turi, 1997; Roylance, 2001). At temperatures above the crossover temperature, the loss modulus (viscous behavior) is more dominant than the storage modulus (elastic behavior). The Intermediate Region Temperature (T_{IR}) is the difference between the crossover temperature and the glass transition temperature, indicating the “length” of the intermediate “transition” region.

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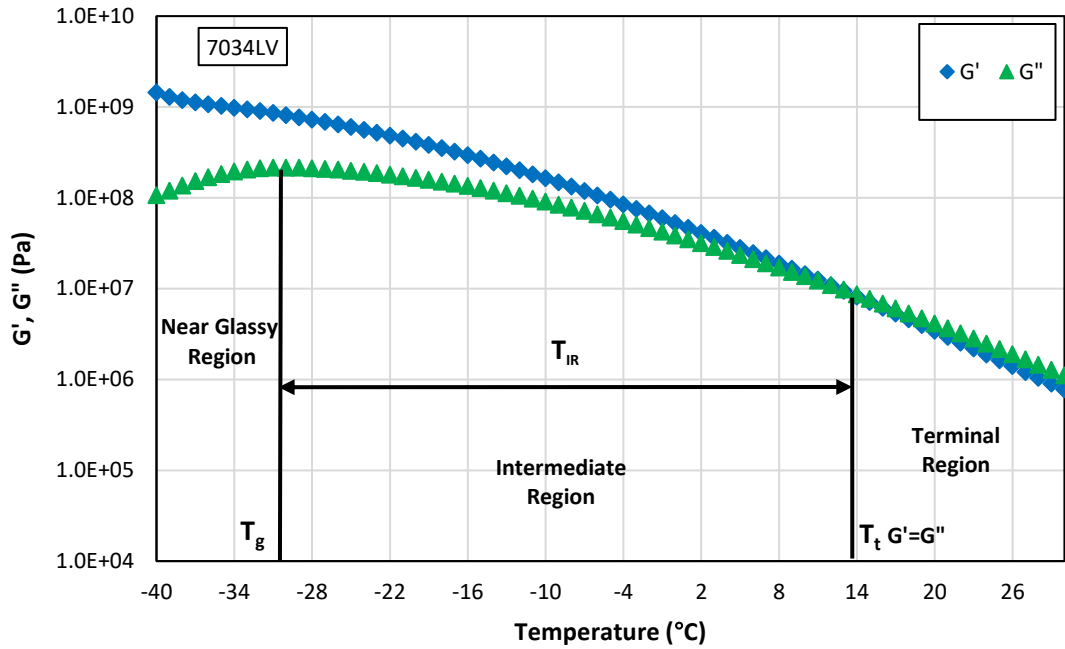


FIGURE 9 T_g , T_t and T_{IR} in G' and G'' Master Curve (Temperature Domain)

Figure 10a, 11a and 12a below show the average T_g , T_t and T_{IR} , figure 10b, 11b and 12b show the change of the T_g , T_t and T_{IR} from STA (LOTAs minus STA) respectively. Error bars show one standard deviation. Generally, T_g , T_t and T_{IR} and the change of these three parameters from STA increase as aging level increases. Similar to the ΔT_c and G-R parameter results, 5834LM and 7034LV typically show lower T_g , T_t and T_{IR} values than other materials after each aging condition, while 7628SM shows higher T_g , T_t and T_{IR} values. Also, from figure 12d, 12e and 12f, 583LM, 7034LV and 7628SM generally show the greater change in T_g , T_t and T_{IR} values compared with others, indicating the higher aging susceptibility.

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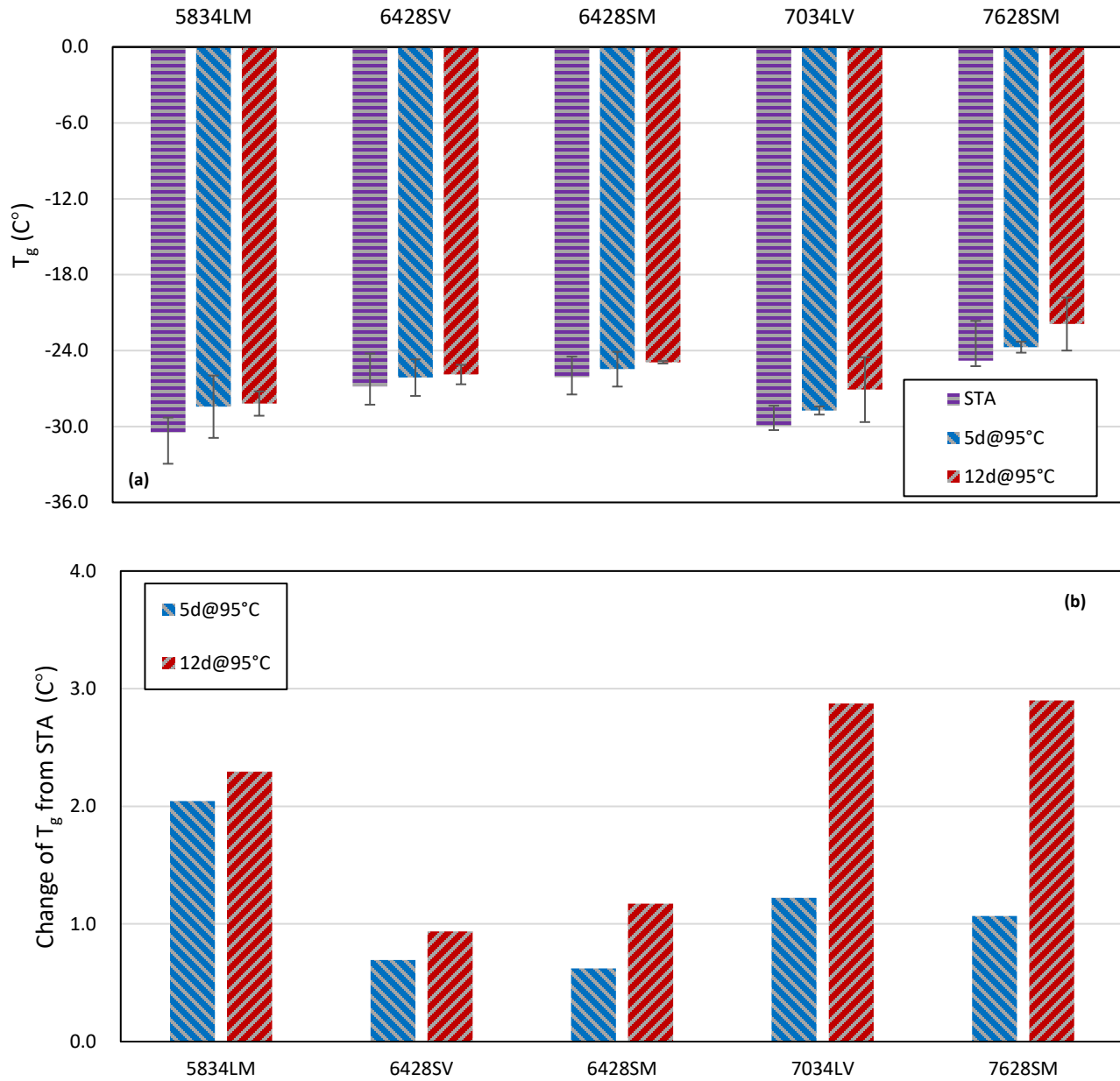


FIGURE 10 a) T_g and b) Change of T_g Parameter for Different Binder Samples from 4mm DSR Tests

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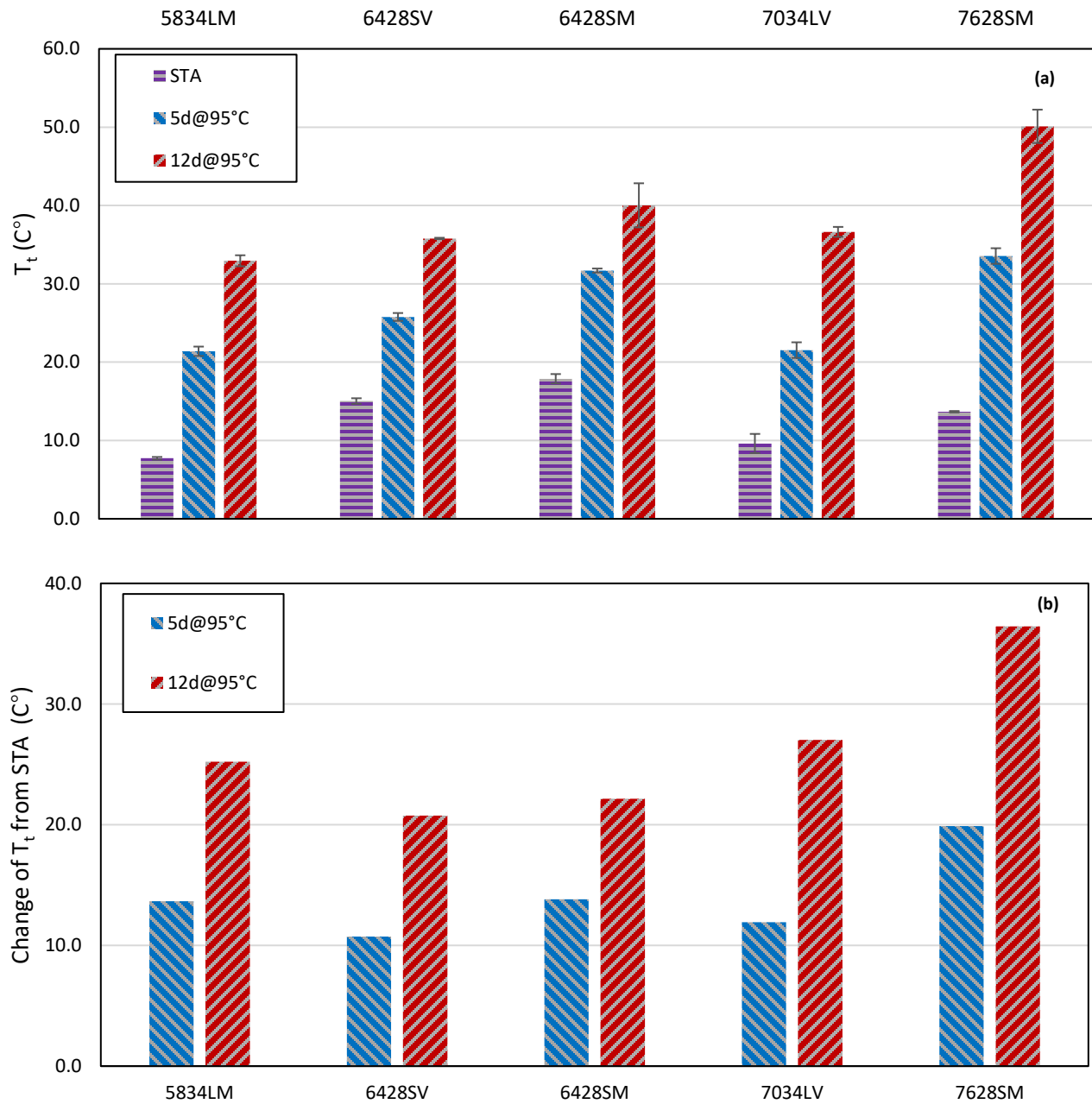


FIGURE 11 a) T_t and b) Change of T_t Parameter for Different Binder Samples from 4mm DSR Tests

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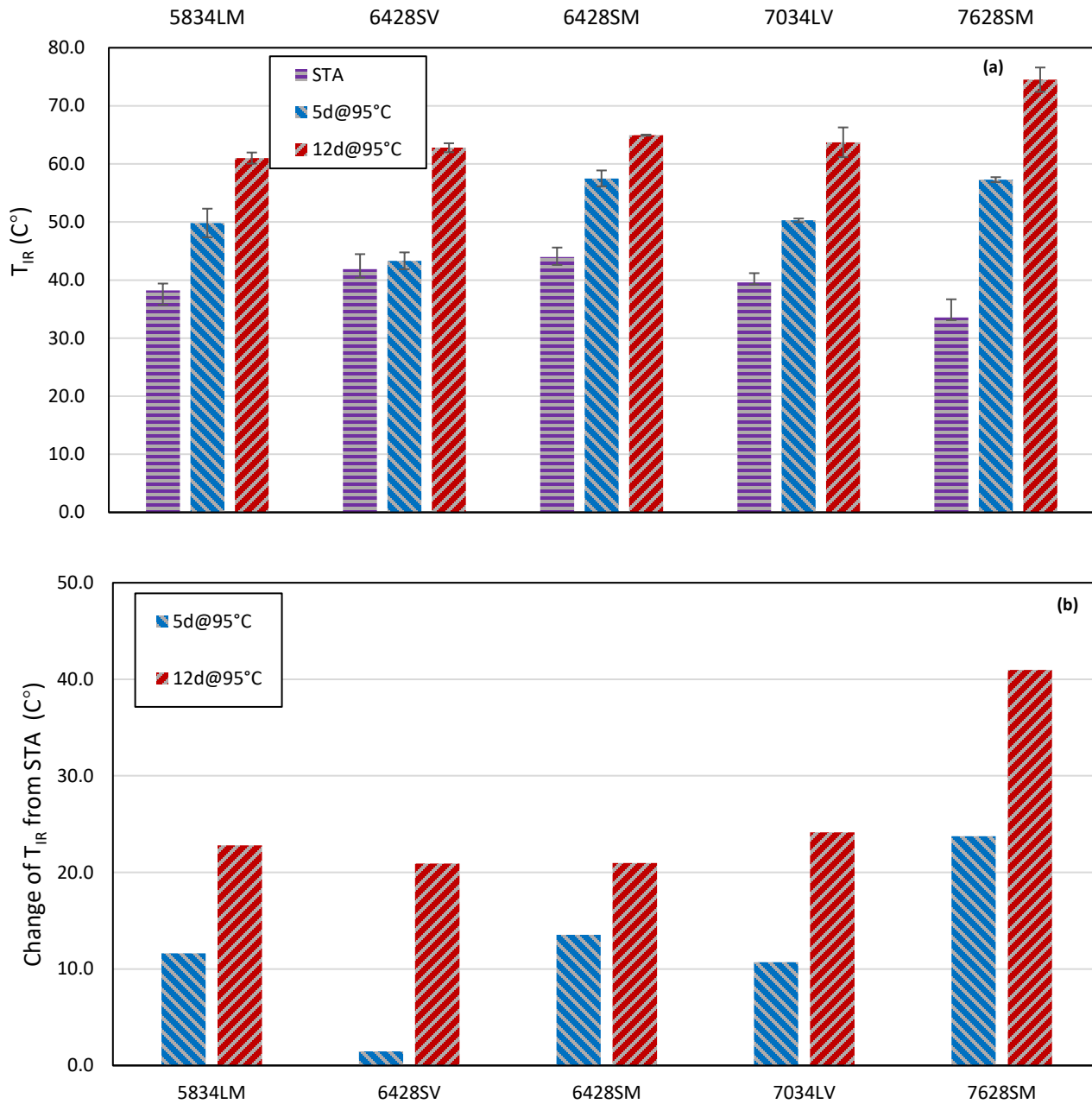


FIGURE 12 a) T_{IR} and b) Change of T_{IR} Parameter for Different Binder Samples from 4mm DSR Tests

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